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DEVELOPMENT OF AN ENVIRONMENTAL CORROSION INDEX FOR ONTARIO

Report No 90-157-K
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ABSTRACT

An environmental corrosion index, which rates the atmospheric corrosivity of locations across Ontario, has been developed. The algorithm arrives at an index rating by comparing successively key environmental parameters (SO_4^{2-}, Cl^-, NH_4^+ in precipitation; Ca in suspended particulates; SO_2 in air; total amount of precipitation) with threshold levels. Useful conductor life, for each rating (1 to 5) has been determined by correlation to average yearly loss in torsional ductility. Average yearly changes in tensile strength and Cormon rating have also been considered. Lifetimes range from 44 to greater than 80 years when using a torsional ductility criterion of 5 turns before failure. The geographical distribution of indices over Ontario identifies the Toronto/Hamilton areas and the south western region as very corrosive, and central and northern Ontario as mildly-corrosive.

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EXECUTIVE SUMMARY

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K.S. Yoshiki-Gravelsins, M. Niewiadomski and H. Leung
Environmental Science Section
Chemical Research Department

Ontario Hydro's Transmission Line Refurbishment Programme concerns the introduction of replacement conductor lines and novel overhead line designs. There is obvious need for improved information on the remaining life of existing facilities. Recently, the Environmental Science Section has investigated atmospheric corrosion of ACSR conductors by determination of the chemical nature of corrosion products, by assembly of an environmental database, and by geographical representations of pollutant levels. In this report, environmental parameters responsible for atmospheric corrosion of conductors are identified and an environmental corrosion index, which is a measure of the atmospheric corrosivity, is presented. Correlations between rates of conductor deterioration (average yearly changes in tensile strength, torsional ductility and Cormon rating) and pollutant levels suggest that the following species should be considered in the environmental corrosion index algorithm: SO_4^{2-}, Cl^-, NH_4^+ in precipitation; Ca in suspended particulates; SO_2 in air; and, total amount of precipitation.

Index ratings are determined by successive comparisons between key environmental parameters and threshold values. These indices have been correlated to average yearly losses in strength, torsional ductility and Cormon rating in order to predict useful conductor life. Good correlation is observed with torsional ductility data; however, correlations with tensile strengths and Cormon values are limited since the former set of data corresponds to aggregate (aluminum and galvanized steel) strengths and the latter set consists of integer values (one to four) which cover the maximum possible range of zinc loss (0 to 100%). Useful conductor lifetime increases from about 30 years to over 80 years, as the atmospheric corrosivity (index rating) decreases and as the criterion for usefulness (e.g., number of turns before mechanical failure) becomes less stringent. Finally, geographical analysis of the index ratings over Ontario indicates high atmospheric corrosivities in the Toronto/Hamilton areas and the south western region and low corrosivities in central and northern Ontario.

The geographical distribution of environmental corrosion indices over Ontario will be instrumental in determining priorities in transmission line replacement. It is expected that as more environmental, mechanical testing and Cormon data become available, the correlation between environmental parameters and useful conductor life will be further improved.

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DEVELOPMENT OF AN ENVIRONMENTAL CORROSION INDEX FOR ONTARIO

1.0 INTRODUCTION

In support of Ontario Hydro's transmission line refurbishment programme [1], the Environmental Science Section is conducting studies to identify pollutants which are responsible for atmospheric corrosion of ACSR transmission line conductors and investigating means to predict the remaining life of these conductors. A preliminary correlation between age of conductor at the time of 32% RTS (rated tensile strength) strength loss and air pollutant levels [2] indicated the need for more complete environmental data and the need to consider combined pollutant effects (e.g., amount of precipitation and SO_2 concentration). More recently, an environmental database which combines meteorological, air quality, precipitation chemistry, and emissions data for southern Ontario [3] has been assembled and a report identifying the corrosion products and corrosion mechanisms of ACSR conductors [4] has been issued. Furthermore, mechanical testing data (tensile strength, torsional ductility) and Cormon rating values (thickness of remaining galvanized layer) are now available as measures of the degree of corrosion of conductors.

The objectives of this study are to (i) develop an environmental corrosion index, which considers key atmospheric pollutants and corresponding threshold levels; (ii) assign index values to sites in Ontario; and (iii) determine the relationship between degree of corrosion and environmental corrosion index, such that useful conductor life can be predicted. The results of this study will be instrumental in meeting objectives of the transmission line refurbishment programme, i.e., establishing the costs, schedules and priorities for introduction of replacement lines and novel overhead line designs.

2.0 DEVELOPMENT OF THE ENVIRONMENTAL CORROSION INDEX

2.1 Geographical Distribution of Corrosion Intensities

The geographical distributions of corrosion and environmental data are presented in the form of isopleths of yearly average conductor deterioration rates and yearly average pollutant levels, respectively, using an NCAR graphics package which is described in detail elsewhere [5]. Results of statistical treatment (number of data points, maximum, minimum and mean values, and standard deviation) of data, within the mapped area, are displayed in each contour plot. Data values are

printed horizontally and are to be distinguished from contour labels. Along the bottom of each figure, the range of contour values and contour interval are also given.

Although the geographical representation is rather dependent on the method of interpolation between data points, and is limited in the case of sparse data, the contour plot displays conveniently local maxima and minima and regional trends in parameter levels. Furthermore, contour plots offer a simple means to compare regional distributions of conductor deterioration and of pollutant levels, and in this way, indicate key environmental factors in the corrosion processes of ACSR conductors.

2.1.1 Rate of Conductor Deterioration

Existing measures of the degree of corrosion of transmission line conductors, in Ontario, include changes in mechanical properties (tensile strength and torsional ductility loss) and changes in induced electric field signals (Cormon rating). Cormon ratings can be determined conveniently for conductors in live-line operation [6]; however, these data are in the form of integer values (one to four) spanning a maximum range of 0 to 100% zinc loss. On the other hand, strength and torsional ductility loss determinations may be conducted on both king and core galvanized steel strands and inner and outer core aluminum strands; however, destructive testing is involved. The data available through the Mechanical Research and Electrical Research Departments of Ontario Hydro are the first set of line measurements, to determine degree of corrosion, since installation of the conductors. Since conductor ages vary from about 20 to 80 years, average yearly losses in strength, torsional ductility and Cormon rating were selected as measures of corrosion intensity. These three parameters were calculated as follows:

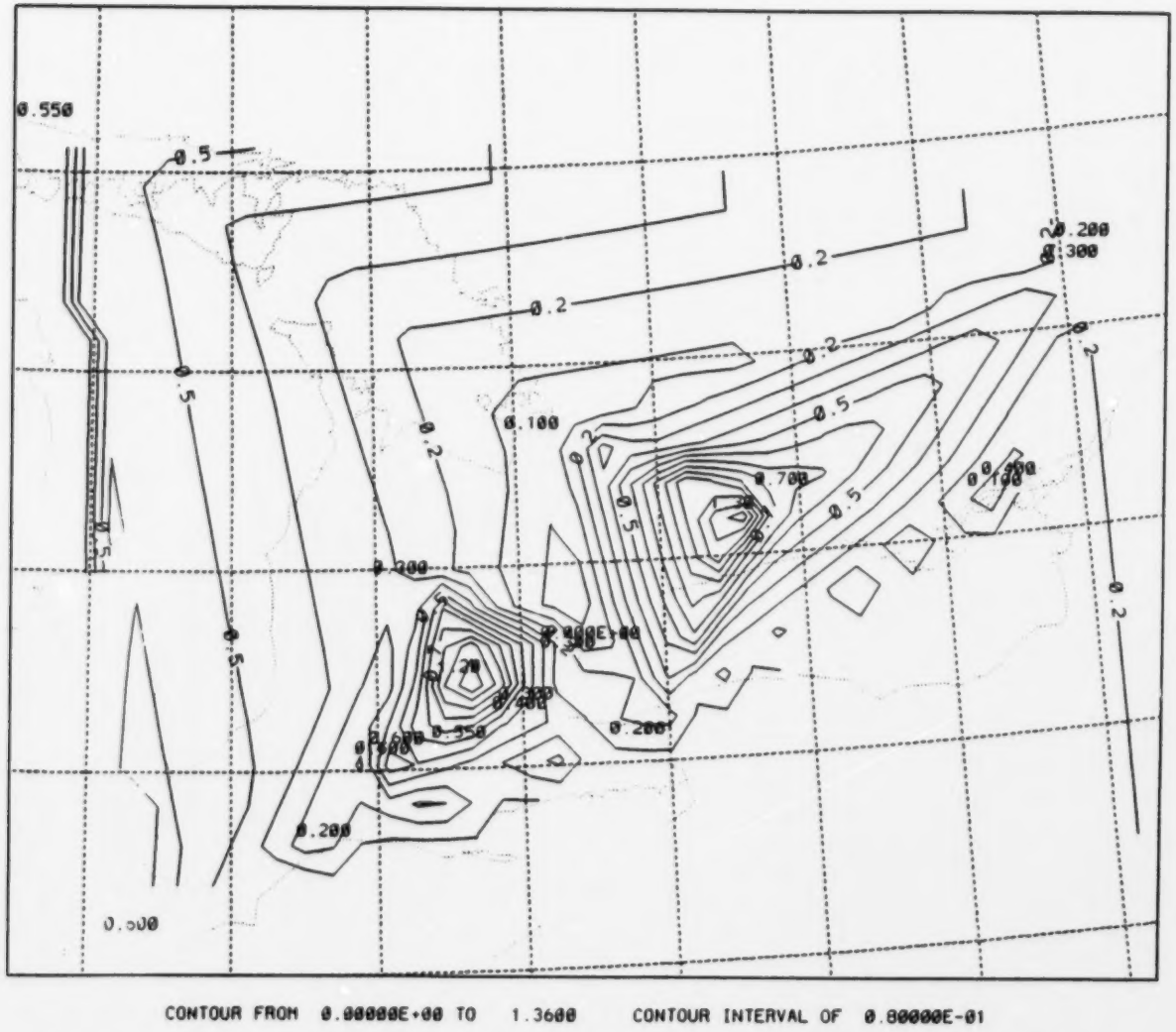
$$\text{Yearly Average Strength Loss (\%/year)} = \frac{\text{Tensile Strength Loss}}{\text{Conductor Age}}$$

$$\text{Yearly Average Torsional Ductility Loss (No. Turns/year)} = \frac{[40 - \text{No. of Turns}]}{\text{Conductor Age}}$$

$$\text{Yearly Average Change in Cormon Rating (1/year)} = \frac{\text{Cormon Rating}}{\text{Conductor Age}}$$

Tensile strength measurements are based on an initial strength of 112% RTS and a typical new conductor demonstrates a torsional ductility equivalent to 40 turns before failure. In treatment of the mechanical testing and Cormon data, it has been assumed that rates of conductor deterioration are linear. This assumption is reasonable considering the ages of conductors and the probability that corrosion product layers have formed, after 20 years.

Figures 1, 2, and 3 illustrate the geographical distributions of degradation rates as measured by tensile strength, torsional ductility, and Cormon rating, respectively. Locations of line sections which were tested are included in Figure 4. The contour plot of rate of tensile strength loss (Figure 1) shows clearly two regions of maxima, near Guelph and Campbellford. A similar contour plot is produced by the rate of torsional ductility loss (Figure 2); however, the maxima near Guelph and Campbellford culminate further east, near Toronto and Kingston, respectively. The contour pattern for change in Cormon rating (Figure 3) is rather complicated with an additional maximum near Hamiiton and minimum near Scarborough. Obvious artifacts produced by the contouring software are visible in all figures over Lake Ontario.


(SL/AGE)
0.550
0.5
0.2
0.100
0.700
0.200
0.300
0.200
0.200
0.200

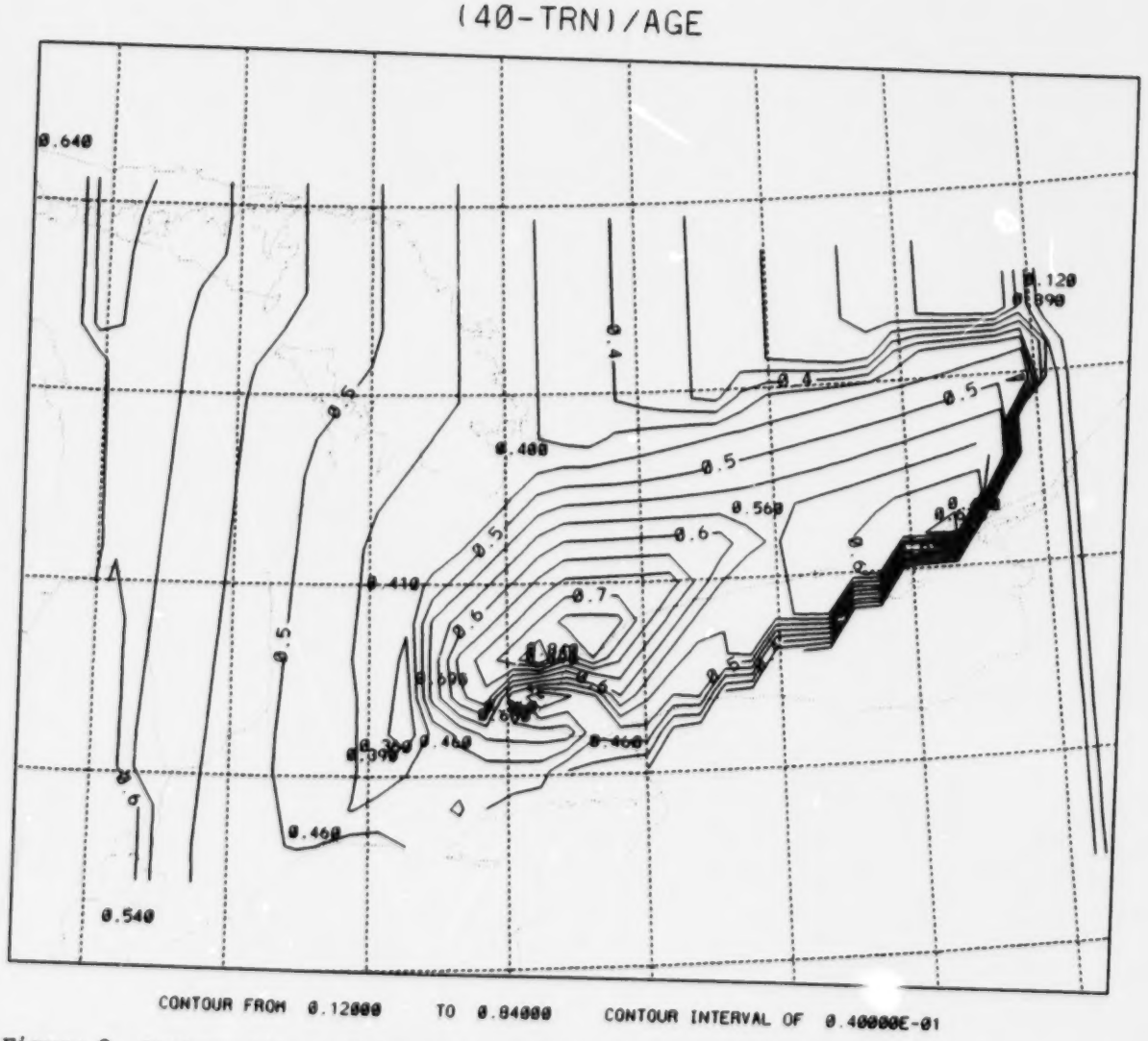


Figure 2 Contour Lines of Average Yearly Loss in Torsional Ductility, (No.turns/year)

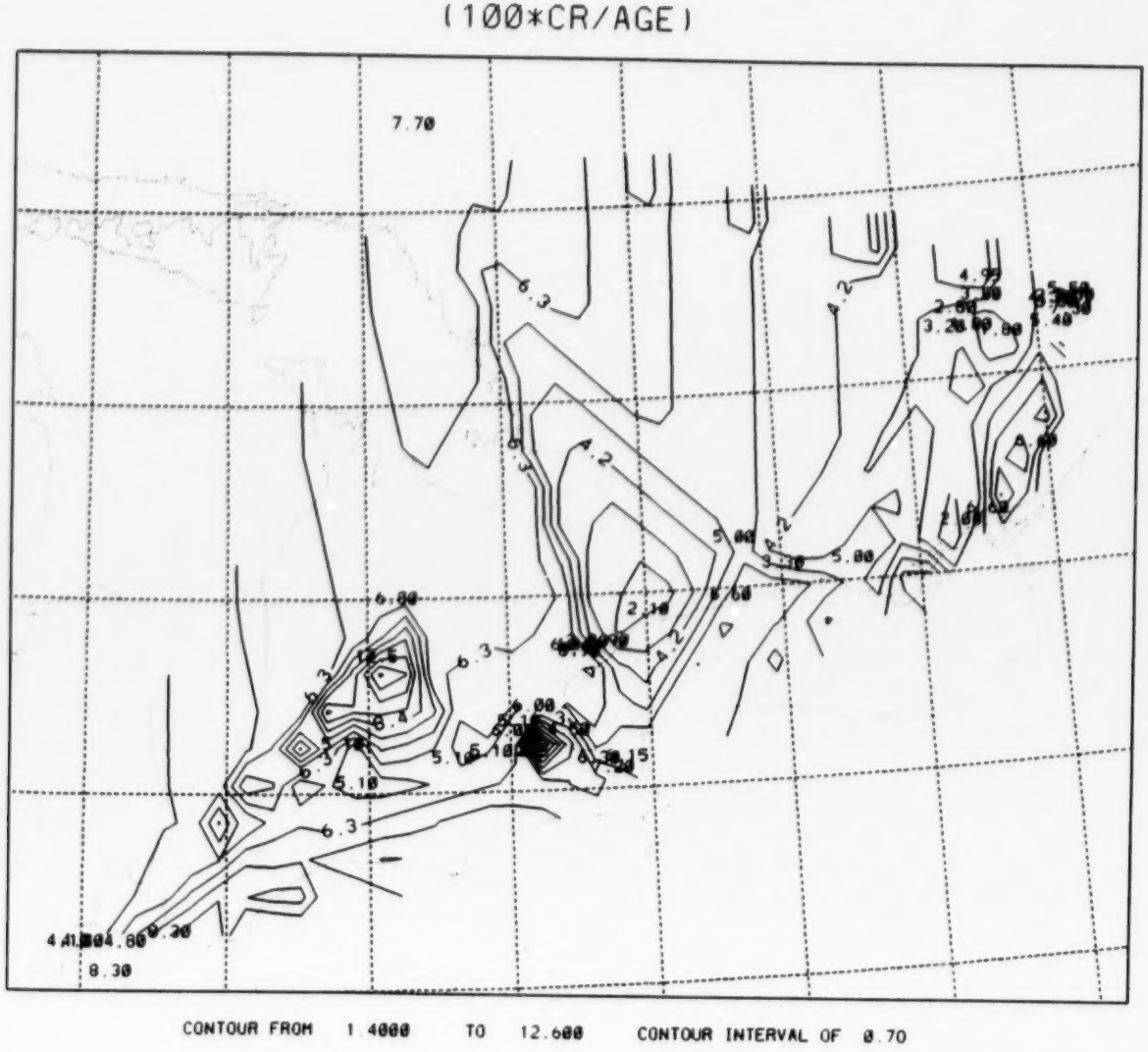


Figure 3 Contour Lines of Average Yearly Change in Common Rating (1/year)

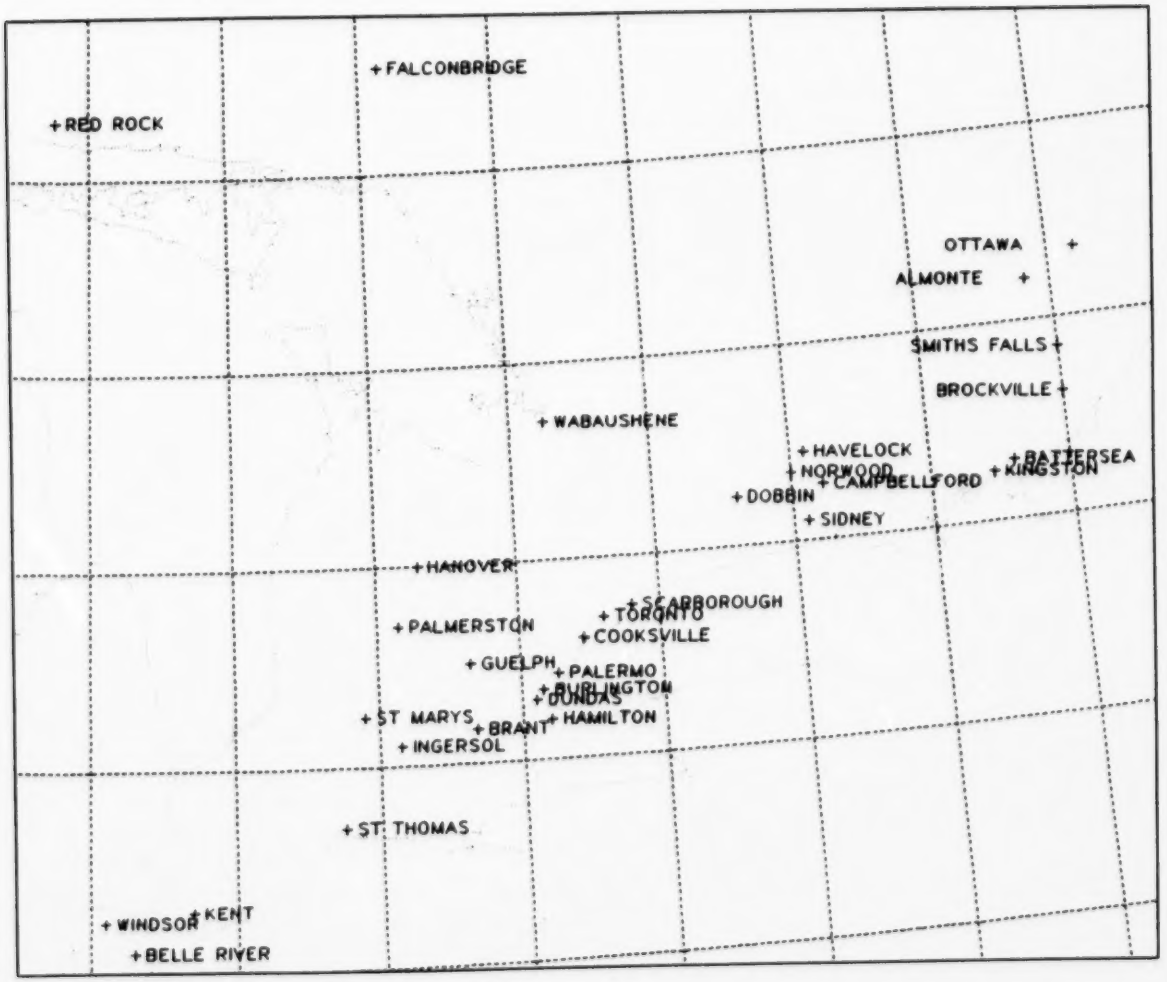


Figure 4 Locations of Tested Conductor Line Sections

2.1.2 *Comparison with Geographical Distribution of Atmospheric Pollutant Levels*

A summary of the geographical distribution of air pollutant levels over the southern Ontario region has been issued [3]. Contour plots consist of yearly, seasonal and monthly average pollutant concentrations in air (SO_2, NO_x, ozone, suspended particulates), and in precipitation (SO_4^{2-}, Cl^-, NO_3^-, NH_4^+, pH, trace metals). In addition, meteorological data (temperature, relative humidity, wind speed and direction, total amount of precipitation), and point source and area emissions levels (SO_2, NO_x, particulates, CO and volatile organic compounds) are displayed. In the present report, contour patterns of average yearly losses in tensile strength, torsional ductility, and Cormon rating (zinc loss) have been compared visually to pollutant isopleths. In many instances, the two mapped areas are not coincident since sites of environmental monitoring stations and sites of tested line sections, vary and give different regional coverage; however, general trends may be observed.

Similarities between contour plots of conductor degradation rates and plots of pollutant levels in precipitation (sulphates, chlorides and ammonia) are greatest, i.e., common display of maxima near Guelph and between Campbellford and Kingston. The geographical distribution of sulphate concentration is shown in Figure 5. The contour plot of calcium in particulates (Figure 6) exhibits a maximum, which extends over a broad area north and northwest of Lake Ontario and which originates near Campbellford. The contour pattern for SO_2 in air (Figure 7) shows high pollutant levels over the Toronto area, similar to that for rate of torsional ductility loss. The significance of these environmental factors in the atmospheric corrosion of ACSR transmission line conductors is discussed in Section 3, Index Ratings and Useful Conductor Life.

2.2 Linear Correlations between Environmental Parameters and Measures of Corrosion Intensities

Linear correlation coefficients of three measures of corrosion intensity with atmospheric pollutants, available in the environmental database [3], are summarized in Tables 1a to 1d. It should be noted that these values do not necessarily represent the isolated effects of each environmental parameter since the other constituent pollutant levels in precipitation or air vary from site to site, as well. Furthermore, values amongst the three measures of corrosion intensity differ because tensile strength, torsional ductility, and Cormon data are not equivalent in terms of accuracy and precision. Reported tensile strength data are measures of the aggregate breaking strengths of aluminum and galvanized steel strands. Since previous studies [7] have shown corrosion rate to be dependent on type of metal, these values are considered least accurate. On the other hand, torsional ductility measurements are available for both inner and outer galvanized steel strands. Data for outer strands, which are more severely corroded, have been selected in this study. The change in Cormon rating, over the lifetime of the conductor, is a rather imprecise measure of corrosion rate since Cormon ratings have integer values of 1 to 4 corresponding to various ranges of zinc loss within the maximum possible range of 0 to 100%.

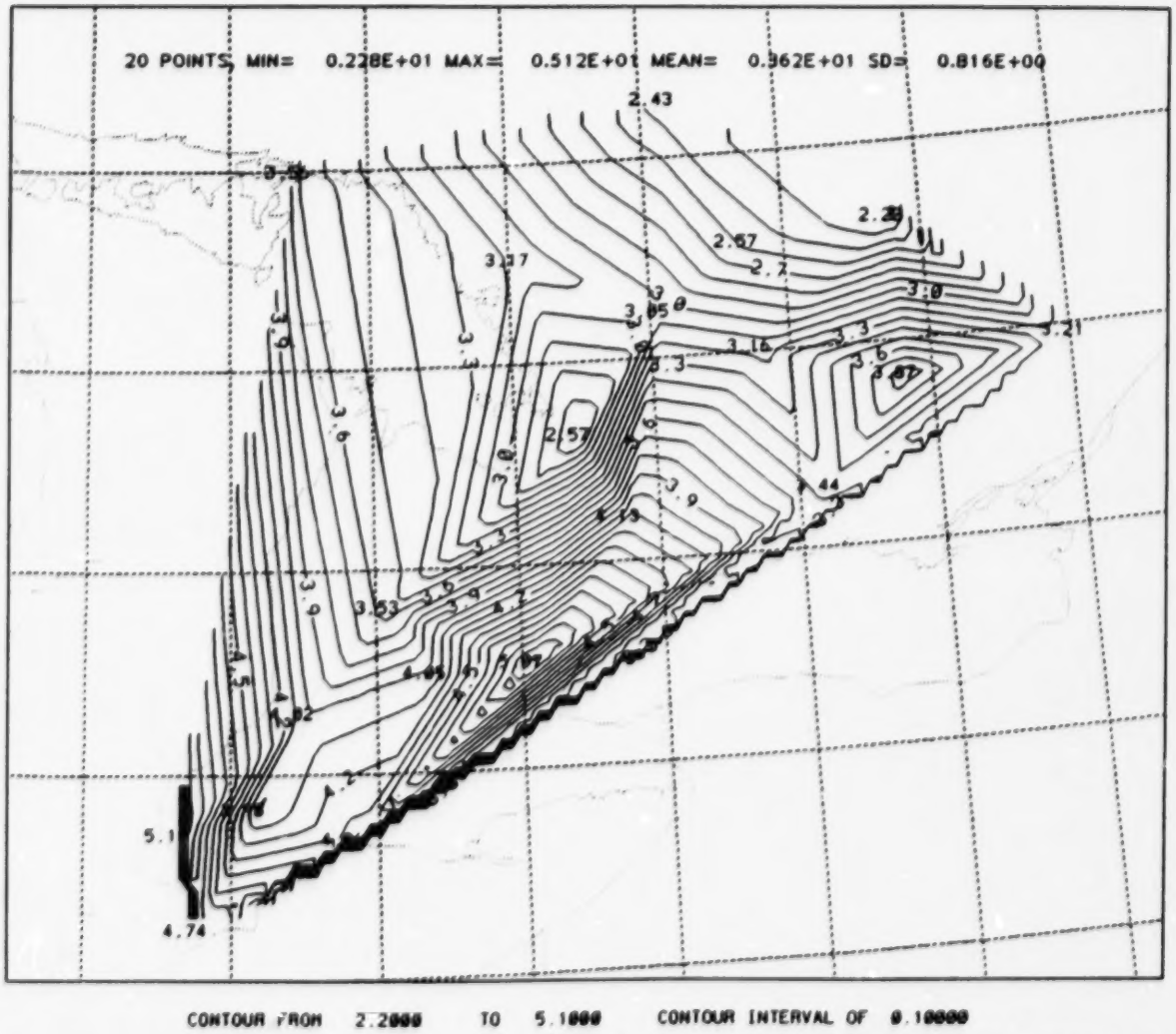

SO4MGL YEARLY AVG
20 POINTS, MIN= 0.228E+01 MAX= 0.512E+01 MEAN= 0.362E+01 SD= 0.816E+00
CONTOUR FROM 2.2800 TO 5.1000 CONTOUR INTERVAL OF 0.10000

Figure 5 Contour Lines of Yearly Average Sulphate Concentrations in Precipitation (mg/L)

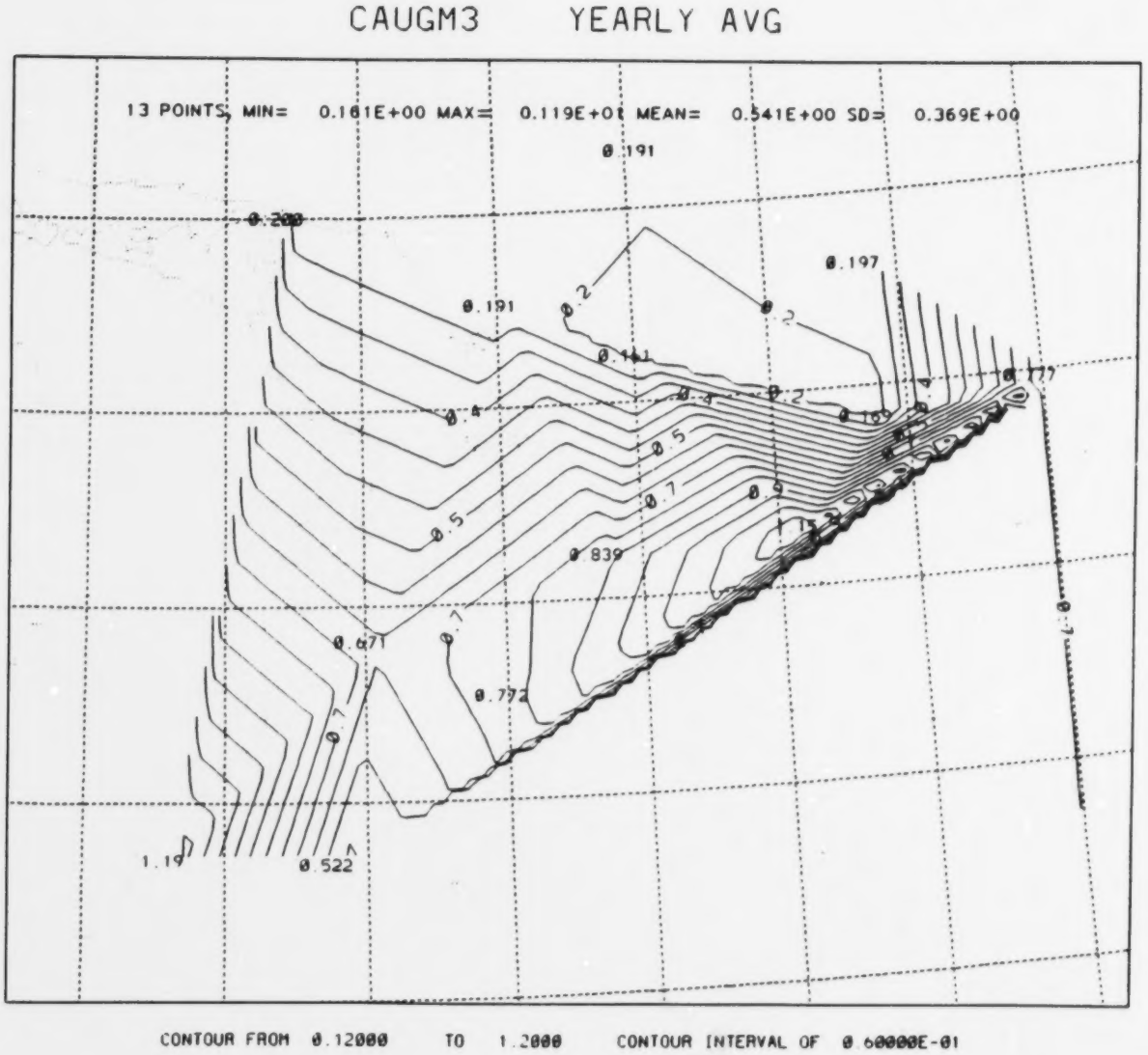


Figure 6 Contour Lines of Yearly Average Calcium Concentrations in Air ($\mu g/m^3$)

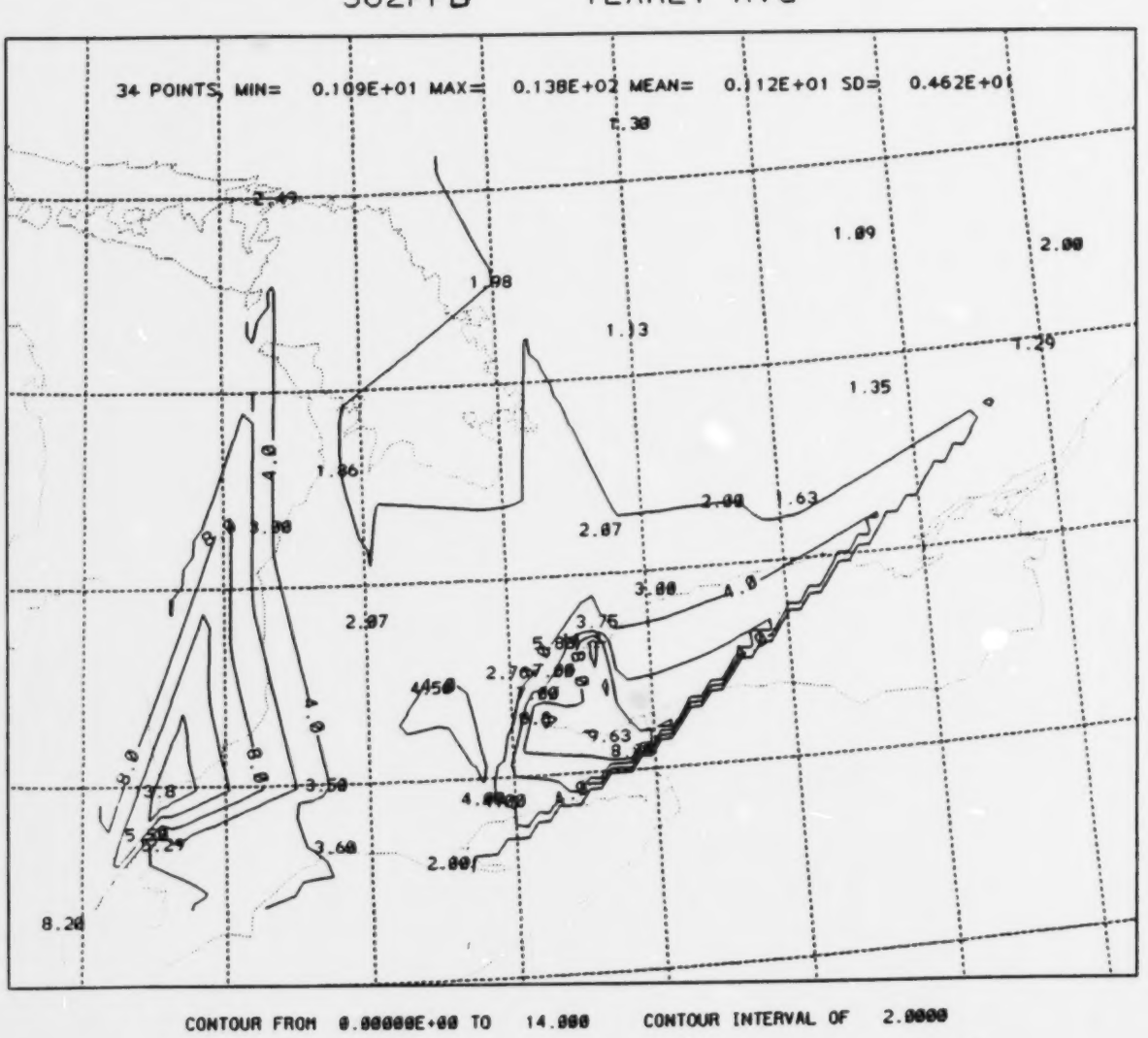

SO2PPB YEARLY AVG
34 POINTS MIN= 0.109E+01 MAX= 0.138E+02 MEAN= 0.112E+01 SD= 0.462E+01
CONTOUR FROM 0.000000E+00 TO 14.000 CONTOUR INTERVAL OF 2.0000

Figure 7 Contour Lines of Yearly Average SO_2 Concenctrations in Air (ppb)

Table 1a
Correlation Coefficients: Pollutants in Air versus Measures of Corrosion Intensity

CORROSION INTENSITY		AIR POLLUTANTS								
Parameter	Description	SO_2	Total S	Total Reduced Sulphur	NO	NO_2	NO_x	CO	O_3	Hydro-carbons
SL/Age	Rate of tensile strength loss	-.25	.07	-.52	.48	.42	.49	-.17	.23	.39
(40-No.Turns)/Age	Rate of torsional ductility loss	.24	.37	-.02	.57	.64	.58	.23	-.16	-.51
100*CR/Age	Change in Cormon Rating	.30	.27	.13	.38	.33	.38	-.11	.24	.05

Table 1b
Correlation Coefficients: Suspended Particulates in Air versus Measures of Corrosion Intensity

CORROSION INTENSITY		AIR POLLUTANTS							
Parameter	Description	SO_4^{2-}	Cl^-	NO_3^-	Ca	Fe	Mn	Pb	TSP
SL/Age	Rate of tensile strength loss	.14	.08	.08	.49	.10	-.06	.16	.32
(40-No.Turns)/Age	Rate of torsional ductility loss	.26	.32	.28	.37	.28	.20	.55	-.25
100*CR/Age	Change in Cormon Rating	.29	.25	.32	-.10	.22	-.04	.28	.37

Table 1c
Correlation Coefficients: Pollutants in Precipitation versus Measures of Corrosion Intensity

CORROSION INTENSITY		POLLUTANTS IN PRECIPITATION									
Parameter	Description	SO_4^{2-}	Cl^-	NO_3^-	PO_4^{2-}	NH_4^+	pH	Ca	Fe	Mn	Pb
SL/Age	Rate of tensile strength loss	.07	-.24	.08	.55	.59	.29	-.18	-.07	-.05	-.04
(40-No.Turns)/Age	Rate of torsional ductility loss	.50	.46	.48	.18	.40	-.16	.49	.12	.44	.49
100*CR/Age	Change in Cormon Rating	.33	.34	.37	.35	.28	-.14	.35	.54	.33	.27

Table 1d
Correlation Coefficients: Meteorological Conditions versus Measures of Corrosion Intensity

CORROSION INTENSITY		METEOROLOGICAL CONDITIONS		
Parameter	Description	Relative Humidity	Total Precipitation	Temperature
SL/Age	Rate of tensile strength loss	.17	-.21	.06
(40-No.Turns)/Age	Rate of torsional ductility loss	.02	-.33	.19
100*CR/Age	Change in Cormon Rating	.25	.25	.23

The linear correlation coefficients listed in Tables 1a to 1d are useful as indicators of environmental factors which may play critical roles in the atmospheric corrosion of line conductors. Pollutants and meteorological parameters which yielded correlation coefficients greater than 0.2 with torsional ductility and which also demonstrated positive values with Cormon rating were considered. X-y scatter diagrams of rate of torsional ductility loss versus pollutant levels were plotted and pollutant parameters were further screened if there was insufficient number (i.e., less than 10 data points) or insufficient distribution of points over a reasonable range of pollutant concentrations. Also, in some cases, degradation rate did not vary with pollutant level, i.e., the fitted curve yielded a correlation coefficient greater than 0.2, but a slope of zero. Suspended particulates in air behaved in this way (see Table 1b); however, calcium was considered since this pollutant species correlated well with torsional ductility and was assumed to represent anionic particulates, as well, by association in the form of salts.

Although good correlations between nitrogen oxides in air and the measures of corrosion intensity are indicated, these pollutants were not considered. The presence of nitrates in the corrosion layers of aluminum and zinc has not been confirmed in previous studies [4,9,10]. It is believed high nitrogen oxide levels (found in industrial environments), merely reflect the presence of other pollutant species (e.g., chlorides) which are involved directly in the corrosion of conductors and which are considered in the environmental corrosion index algorithm.

SO_2 in air was selected rather than 'total sulphur' since the effects of sulphates in particulates in air are considered separately.

It is evident that there is fairly good correlation between measures of corrosion intensity (changes in torsional ductility and Cormon rating), and pollutant levels in precipitation. Although there is mention of a catalytic effect by manganese in the literature [8], the concentration levels and range are limited in this study (0.0026 to 0.0080 mg/L). Therefore, trace metals were ignored. Calcium was also not considered since the relatively high correlation coefficient for calcium is most likely in response to the presence of more aggressive sulphate and chloride species, which may be associated with Ca^{2+} ions. As mentioned previously, the absence of nitrogen-bearing corrosion products indicates that NO_x levels in air and NO_3^- concentrations in precipitation are secondary in importance.

Finally, a strong negative correlation between change in torsional ductility and precipitation is indicated.

Plots of rate of torsional ductility loss, (40-No. of Turns)/Age, against key environmental parameters, and best linear fit curves are presented in Figures 8 to 13. These parameters include yearly average concentrations of: sulphate, chloride and ammonium ions in precipitation; suspended calcium particulates in air; SO_2 in air; and total amount of precipitation.

3.0 INDEX RATINGS AND USEFUL CONDUCTOR LIFE

3.1 Environmental Corrosion Index Algorithm

In the development of an environmental corrosion index algorithm, chemistry of corrosion products and knowledge of corrosion mechanisms must also be applied in order to select environmental criteria. The results of a literature study [11] and analysis of corrosion layers on conductors using various spectroscopic techniques [4] clearly support a corrosion mechanism which involves attack

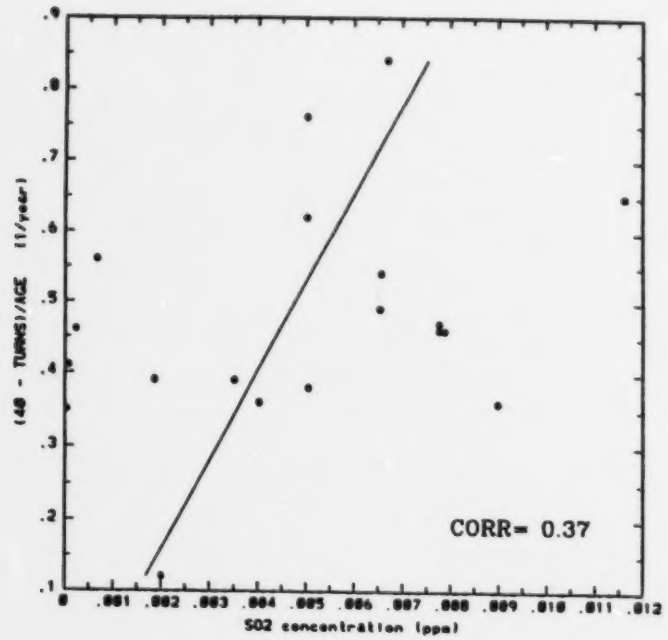


Figure 8 Average Yearly Loss in Ductility (y^{-1}) versus SO_2 Concentration (ppm) in Air

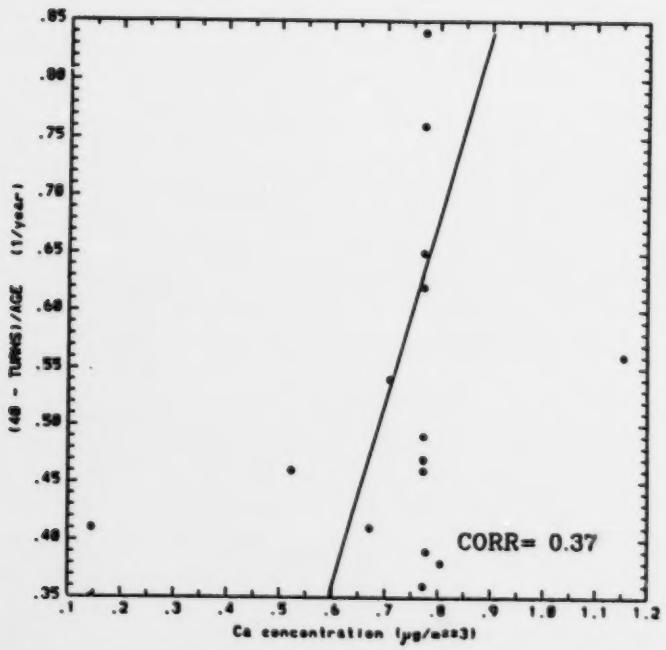


Figure 9 Average Yearly Loss in Ductility (y^{-1}) versus Calcium Concentration ($\mu g/m^3$) in Air

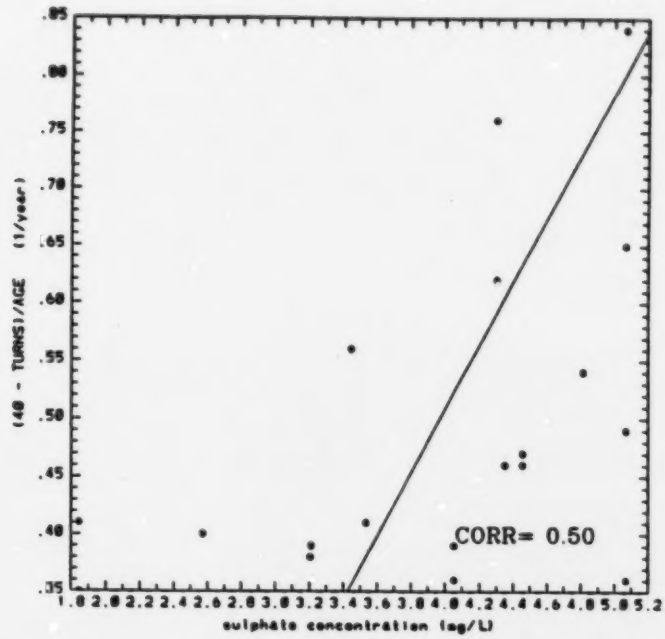


Figure 10 Average Yearly Loss in Ductility (y^{-1}) versus Sulphate Concentration in Precipitation (mg/L)

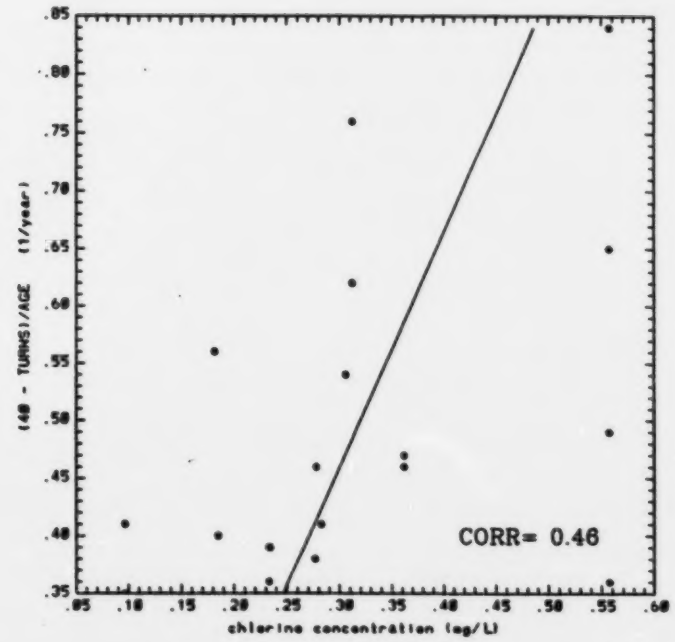


Figure 11 Average Yearly Loss in Ductility (y^{-1}) versus Chlorine Concentration in Precipitation (mg/L)

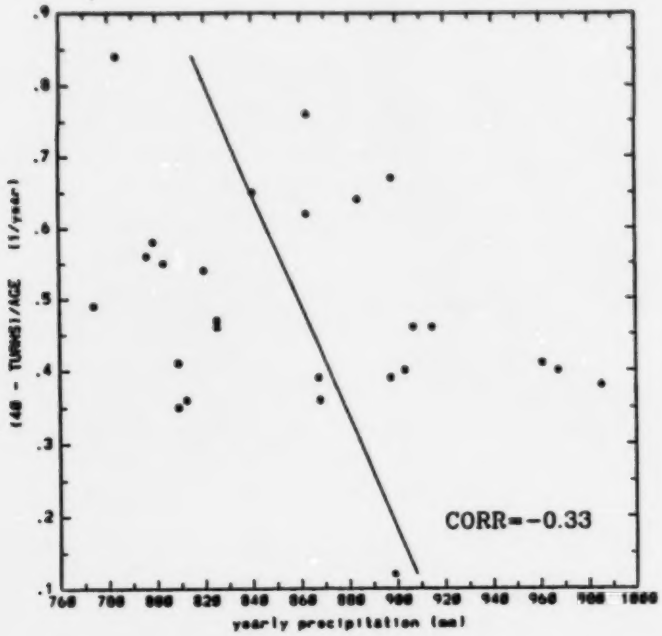


Figure 12 Average Yearly Loss in Ductility (y^{-1}) versus Ammonia Concentration in Precipitation (mg/L)

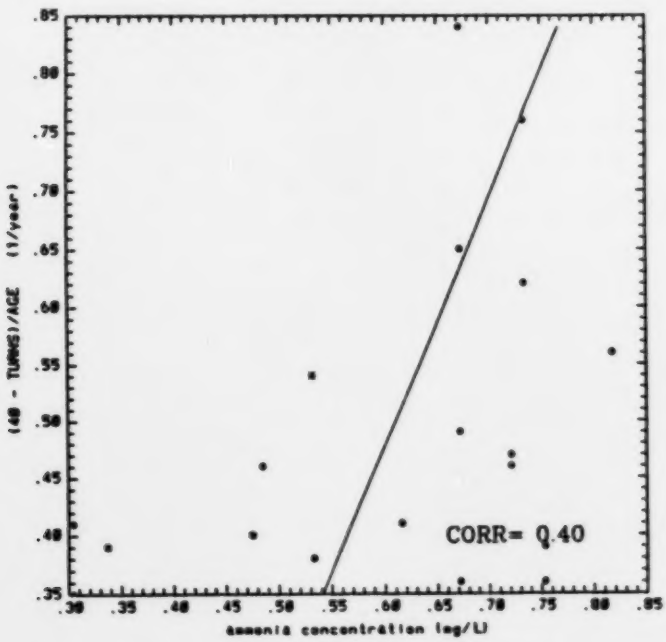


Figure 13 Average Yearly Loss in Ductility (y^{-1}) versus Total Amount of Precipitation (mm/y)

by sulphate and chloride species. The correlation study, above, indicates that these ions in precipitation, rather than air, are most important. In the corrosion of aluminum, sulphate attack is favoured kinetically while chloride ions are responsible for pitting [12]. SO_2 in air is also a source of sulphate ions, in the presence of moisture and oxidizing agents.

Suspended particulates in air are suspected of enhancing corrosion by supplying ionic species and by establishing differential oxygen (aeration) cells on the conductor surface [13]. Since total suspended particulate (TSP) data are limited in regions where mechanical testing and Cormon values are available, calcium in particulates has been selected as a criterion in the algorithm.

Ammonia solutions are known to have low surface tensions and thus, exhibit good wetting behaviour [14]. Availability of electrolyte, which is necessary for ionic transfer during electrochemical reactions of corrosion, is determined by the relative humidity, temperature, and amount of precipitation. Since all conductors studied are advanced in age (greater than 20 years) and have experienced a loss in cross-sectional area (approximately 10 percent), it is assumed that inner wires are well-wetted by (i) trapped moisture between conductor strands and (ii) the presence of deliquescent corrosion products, such as chlorides. High levels of precipitation are believed to be beneficial since dissolution and washing away of aggressive pollutant species and corrosion products occurs. The effects of an increase in temperature: enhanced rate of corrosion but also loss of electrolyte by evaporation; are not considered since correlations with conductor degradation are poor.

Acidic conditions are known to result in the breakdown of passivating product layers, such as zinc hydroxide and hydroxycarbonate [10]. pH is not considered in the algorithm for Ontario since all available precipitation data are within the pH range, 4.07 to 4.69, and are clearly acidic.

A corrosion severity index is in use by the USAF, for anticipating corrosion-related damage to aircraft and for scheduling appropriate repairs and maintenance actions [15]. An environmental corrosion index algorithm has been developed for Ontario based on the pollutant criteria described in the present report. The index is a single parameter which represents the corrosivity of the local environment. The algorithm arrives at an index rating by comparing successively key environmental factors with corresponding threshold values. Each critical concentration has been determined statistically from the mean value plus thirty percent of the difference between the 50th and 100th percentiles. Since a high level of precipitation retards conductor corrosion, a threshold value less than the mean has been selected. The algorithm, depicted in Figure 14, first considers sulphate concentration in precipitation, leading either to severe corrosion ratings (3 to 5) or less severe (1 to 3). If the concentration is greater than or equal to the threshold level, pollutant concentrations are compared with thresholds for chloride in precipitation and total amount of precipitation. "Pass" values for both factors leads to the most corrosive rating of 5. If either factor is below the critical level, NH_4^+ concentration in precipitation is considered. In the event the initial test for sulphate fails, calcium in suspended particulates and total amount of precipitation are compared to threshold values. An environmental corrosion index of 3 results if both factors are acceptable; however, if either fails, the concentrations of SO_2 in air and NH_4^+ in precipitation are evaluated and a rating of 1 or 2 results.

Environmental Corrosion Indices have been calculated for sites at which Cormon and mechanical testing data for conductors are available. Correlations between index ratings and average yearly changes in torsional ductility, tensile strength and Cormon rating, and predictions of useful conductor life are presented below.

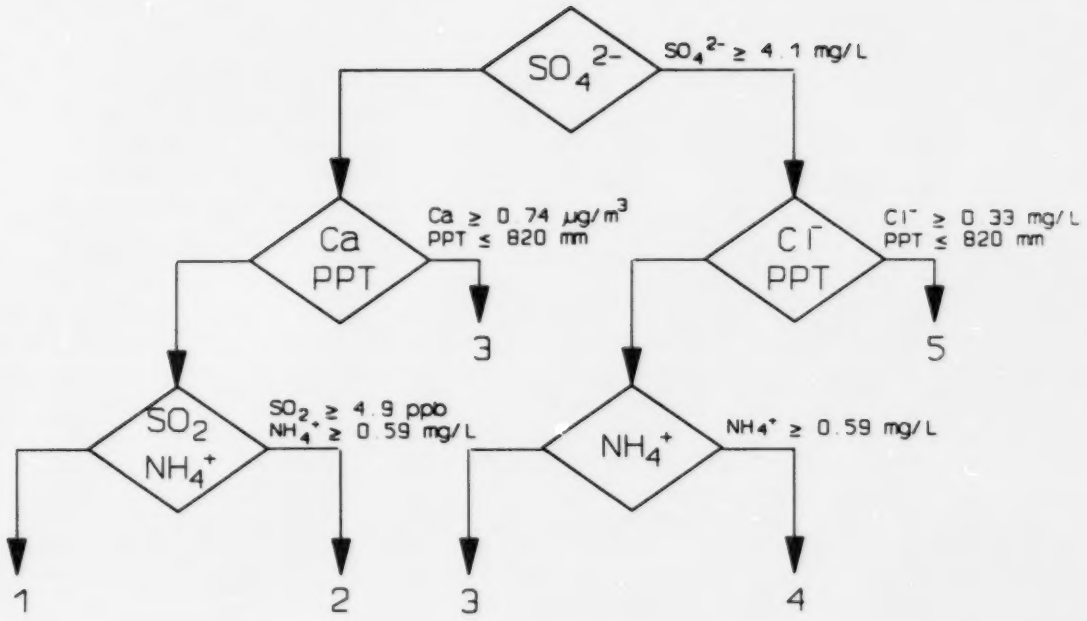


Figure 14 Environmental Corrosion Index Algorithm

SO_4^{2-}, Cl^-, NH_4^+ = ionic concentrations in precipitation (mg/L)
Ca = concentration in suspended particulates (µg/m³)
SO_2 = concentration in air (ppb)
PPT = total yearly precipitation (mm)

3.2 Predictions of Useful Conductor Life

Figures 15 to 17 illustrate correlations between environmental corrosion index and average yearly loss in torsional ductility ((40-No. of turns)/conductor age), average yearly loss in tensile strength (% strength loss/conductor age), and average yearly change in Cormon rating (Cormon rating/conductor age), respectively. The linear fit is best with the torsional ductility data, followed by Cormon rating and then tensile strength. As discussed previously, the variable, yearly change in Cormon rating is imprecise. For example, the yearly change in Cormon rating for an 80 year old conductor, rated at 4, may vary from $5x10^{-2}$ to $8x10^{-2}$ y^{-1} (see Figure 17) depending on the age (i.e., 80 to 40 years) at which zinc loss first rated 80%. The correlation with tensile strength is limited since these data correspond to aggregate breaking strengths of aluminum and steel strands. Therefore, the correlation between environmental corrosion index and torsional ductility (Figure 15) was selected to predict the useful life of ACSR transmission line conductors. In the linear regression analysis of these data, the outlying point (Horning Mt. Jct to Burlington (5, 0.36)) was not considered. Sources of uncertainty are discussed later in this section.

Predicted conductor life, for each environmental corrosion index rating (1 to 5), has been calculated from the correlation equation,

$$y = 0.10x + 0.27$$

where y is the average yearly loss in torsional ductility, (40-No. turns)/age, and x is the index rating. Conductor ages are listed in Table 2 for mechanical failure at 5, 10 and 15 turns. Confidence limits corresponding to one standard deviation are also presented. As the criterion for usefulness (number of turns) becomes more stringent, predicted lifetimes decrease. Useful conductor lifetimes also decrease as the atmospheric corrosivity (index rating) increases.

Table 2 Correlation between Environmental Corrosion Index and Conductor Age

Environmental Corrosion Index	Predicted Conductor Life (years)*		
	Age at 5 turns	Age at 10 turns	Age at 15 turns
1	>80	80 ± 10	70 ± 10
2	75 ± 8	64 ± 7	53 ± 6
3	60 ± 7	52 ± 6	43 ± 5
4	51 ± 6	41 ± 5	34 ± 4
5	44 ± 5	37 ± 4	31 ± 3

* limits correspond to one standard deviation

The correlation between predicted conductor life and environmental corrosion index for Ontario is subject to a few uncertainties. Firstly, the number of locations for which the environmental corrosion index could be calculated was rather limited because complete sets of environmental data were not available. Data were compiled from a variety of sources, e.g., Air Quality Monitoring Programme of the Ontario Ministry of the Environment (pollutant levels in air) and Canadian Climate Centre of AES (meteorological data), which utilized independent monitoring station networks. Secondly, it was difficult to locate accurately (within 5 km) sites of tested lines. In many instances, the line section extended over a distance of up to 50 km, and only the worst case value (i.e., greatest strength loss or torsional ductility loss) was reported for each line section.

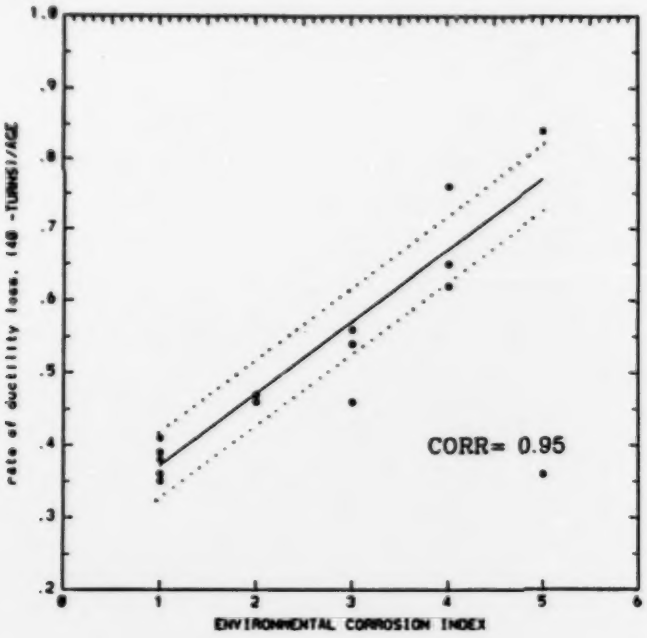


Figure 15 Average Yearly Loss in Ductility (y^{-1}) versus Environmental Corrosion Index
$y=0.10x + 0.27$, $\sigma_y = 0.049$

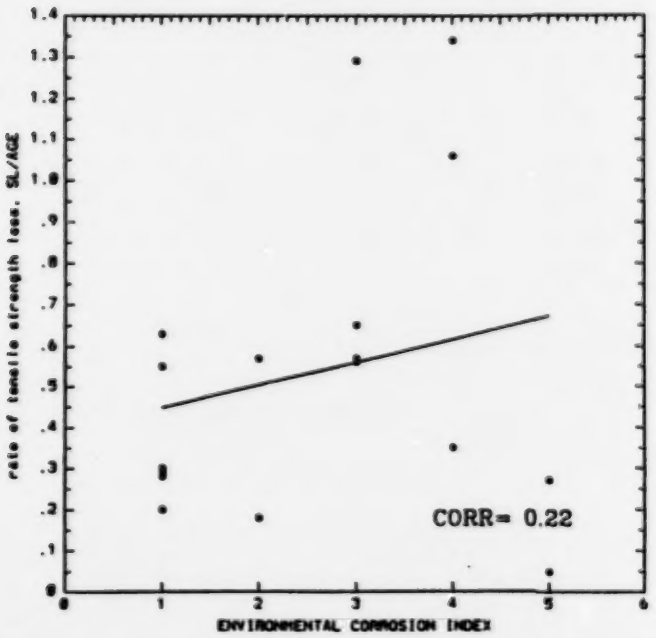


Figure 16 Average Yearly Loss in Tensile Strength (%/y) versus Environmental Corrosion Index (based on an average initial rated tensile strength of 112% RTS)

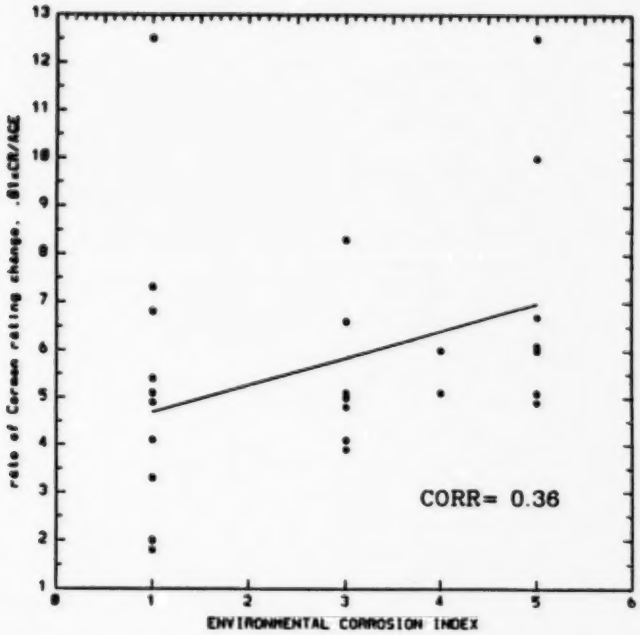


Figure 17 Average Yearly Change in Corrosion Rating (y') versus Environmental Corrosion Index

Finally, the sites for which mechanical testing and Cormon data were available did not necessary coincide with locations of environmental monitoring stations. In some instances, levels of atmospheric pollutants for a particular line section were estimated by using weighted concentrations from neighbouring environmental monitoring stations which were located at a distance of 50 km. There is an obvious need for more environmental, mechanical testing and Cormon data at other locations to refine the correlation between conductor life and environmental corrosion index. It should also be noted that the correlation is limited to the range of conductor ages and range of torsional ductility measurements of the test data, i.e., 21-79 years and 1-25 turns, respectively.

Finally, the environmental data correspond to environmental conditions of fairly recent years and do not necessarily represent conditions over the lifetimes of conductors.

3.3 Environmental Corrosion Indices for Ontario

Environmental Corrosion Indices for southern Ontario are displayed in Figure 18. Corrosive atmospheres are located over the Toronto/Hamilton areas and in the south western region. In general, central and northern Ontario have an index rating of 1 indicating only mildly-corrosive conditions.

It should be noted that application of the algorithm to determine Environmental Corrosion Indices is restricted to climates similar to that of Ontario. Maximum, minimum and mean pollutant levels are listed in Appendix I. Most notable climatic characteristics include: (i) acidity of precipitation (mean pH is between 4.07 to 4.69); and (ii) chloride concentrations in air and precipitation which are below coastal values. For example, in coastal areas, large chloride particles in air are more important than small particles which serve as condensation nuclei for cloud droplets and are dispersed over great distances from the sea [15].

4.0 SUMMARY

Geographical distributions of the rates of degradation of transmission line conductors, as measured by tensile strength, torsional ductility and Cormon rating, have been displayed over southern Ontario using a contouring software package. Comparison with similar plots of pollutant levels have indicated key environmental factors (SO_4^{2-}, Cl^-, NH_4^+ in precipitation; Ca in suspended particulates; SO_2 in air) in the corrosion processes of ACSR conductors. These results have been confirmed by linear correlation studies of environmental parameters (meteorological conditions, precipitation chemistry and air quality data) and conductor deterioration rates.

An environmental corrosion index rating, which measures the corrosivity of the local environment, has been developed based on the pollutant criteria described above. The algorithm arrives at an index rating by comparing successively key environmental parameters with threshold values. The useful conductor life, which corresponds to each rating (1 to 5) has been determined by correlation to average yearly loss in torsional ductility. Lifetimes range from 30 to greater than 80 years depending on the environmental corrosion index rating and the criterion for usefulness. As more environmental, mechanical testing and Cormon data become available, prediction of useful conductor life will be more precise.

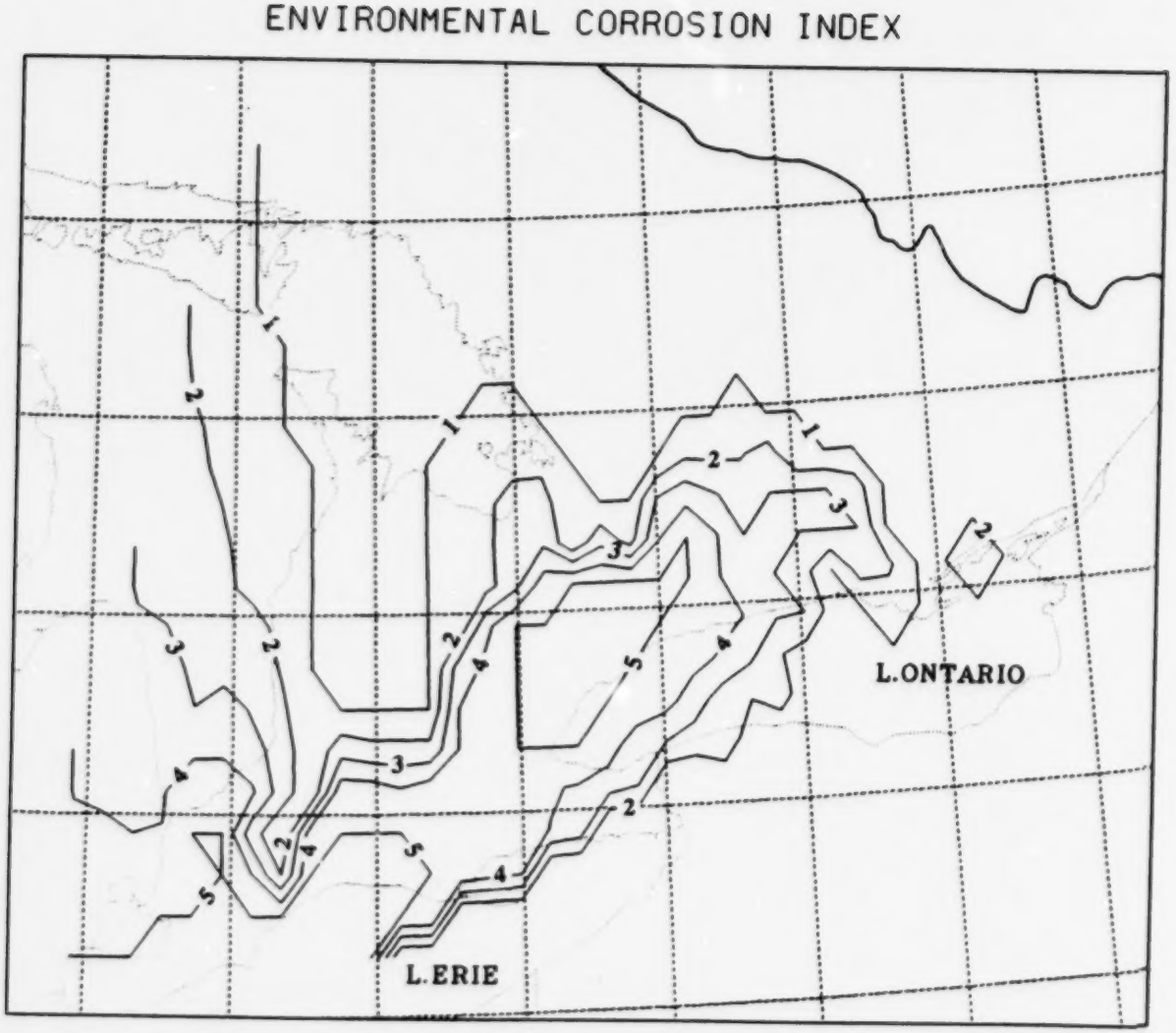


Figure 18 Environmental Corrosion Indices for Ontario

A contour plot of the indices over Ontario has identified the Toronto/Hamilton areas and the south western region as very corrosive, and central and northern Ontario as mildly-corrosive. This geographical distribution of indices over Ontario is very informative and will provide a guideline for introduction of replacement transmission lines.

5.0 RECOMMENDATIONS

In testing the algorithm for the environmental corrosion index, it became apparent that more confidence could be added to the index by expanding the limited data set and improving knowledge concerning the exact locations of line measurements. As more environmental, mechanical testing, and Cormon measurements are made, refinement of the index is expected such that atmospheric corrosivity ratings are available on a finer scale than the 50 km square grid used previously.

The importance of point and line source emissions has been illustrated by variation of the degree of conductor deterioration over short distances (1 to 2 km). Dispersion modelling studies are necessary to predict pollutant concentrations in the vicinity of sources (e.g., highway, lime plant) and in areas remote from environmental monitoring stations. These studies will provide more accurate data to be used in establishing relationships between corrosion intensity and environmental parameters. In particular, road salts, sources of chloride, are known to enhance corrosion, and have also been linked to contamination flashover of insulators. Concentration fields (vertical and horizontal profiles) and size distribution of road salts should be established at sites near highways where Cormon and mechanical testing data are available.

Correlations between atmospheric corrosivity and conductor deterioration may be further improved by consideration of a "time of wetness" parameter which measures the period of precipitation plus the period over which the relative humidity is greater than a critical value (e.g., 80%). The presence of a moisture film is expected to correlate well with degree of corrosion since electrolyte is necessary for ionic transfer in aqueous corrosion.

It has been noted that the environmental data set covers the last 10 to 30 years and may not represent accurately conditions over the entire lifetime of the conductors (approximately 40 to 80 years). In addition, atmospheric conditions are expected to change further during the lifetime of replacement lines, with reductions in SO_2 and NO_x emissions. These effects on corrosion rate of transmission line conductors should be established by accelerated testing of cables which have been previously exposed to industrial, urban and rural environments. An evaluation of damage functions, available in the literature, which describe cause-effect relationships between environmental parameters and degree of corrosion, may also be useful in modifying the environmental corrosion index to account for changing environmental conditions.

Finally, as more mechanical testing and Cormon data become available, the corrosion of 115 kV versus 230 kV lines, single versus double layer aluminum conductors, and round versus new compact conductor designs should be investigated.

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APPENDIX I

POLLUTANT LEVELS OVER SOUTHERN ONTARIO

Air Pollutants ($\mu g/m^3$)

Species	Maximum	Minimum	Mean	Std Dev	No.
SO_2 (ppb)	13.8	1.09	1.12	4.62	34
Total S	9.25	2.08	4.33	1.88	13
NO (ppb)	85.0	1.00	28.0	19.8	21
NO_2 (ppb)	40.0	4.00	23.3	8.31	25
NO_x (ppb)	125	28.0	54.6	24.0	20
CO	4.40	0.100	1.31	0.991	24
O_3 (ppb)	35.8	11.2	20.0	5.98	28
Hydrocarbons	2.63	1.43	1.94	0.320	10
SO_4^{2-}	6.46	1.75	3.74	1.17	13
Cl^-	0.814	0.196	0.390	0.161	13
NO_3^-	6.09	1.17	2.81	1.47	13
Ca	1.19	0.161	0.541	0.369	13
Fe	0.249	0.0745	0.132	0.0537	13
Mn	0.0127	0.00382	0.00776	0.0033	13
Pb	0.123	0.0203	0.0438	0.0254	13
TSP	108	39.0	70.6	17.7	27

Pollutants in Precipitation (mg/L)

Species	Maximum	Minimum	Mean	Std Dev	No.
SO_4^{2-}	5.12	2.28	3.62	0.816	20
Cl^-	0.557	0.100	0.225	0.104	20
NO_3^-	3.20	1.44	2.46	0.455	20
PO_4^{3-}	0.754	0.00930	0.0298	0.0204	20
pH	4.69	4.07	4.33	0.143	20
Ca	1.69	0.165	0.598	0.382	20
Fe	0.216	0.0351	0.0831	0.0445	20
Mn	0.00800	0.00260	0.00459	0.00167	20
Pb	0.0118	0.0047	0.00717	0.00164	20
NH_4^+	0.817	0.226	0.487	0.159	20

Meteorological Conditions

Parameter	Maximum	Minimum	Mean	Std Dev	No.
Rel Hum(%)	79.4	70.3	75.5	2.55	17
Precip.(mm)	1190	674	857	87.0	373
Temp(°C)	9.70	3.36	6.66	1.44	268